Linearization Techniques for CMOS LNAs: A Tutorial

Edgar Sánchez-Sinencio

Analog and Mixed Signal Center
Outline

• Motivation
• Linearization Techniques
• New Issues for Wideband Applications
• LNA Linearization in Deep Submicron Process
• Remarks for High Linearity LNA Design
Why Study LNA Linearization?

- Plethora of wireless standards occupying narrow frequency bands
- Trend in radio research: eliminate the expensive external front-end module (FEM)
  - A highly linear receiver is required
  - As the first block in receiver, the LNA must be sufficiently linear to suppress interference and maintain high sensitivity
Anything Special for LNA Linearization?

- Must be simple, consume minimum power, preserve the gain, input matching, and low NF
- Many traditional linearization techniques are not feasible for LNAs
  → LNA linearization is more challenging than baseband circuits linearization
- Volterra-series is usually used to analyze the frequency-dependent distortion
LNA Linearization Techniques

• A weakly nonlinear amplifier is characterized by:

\[ Y = g_1 X + g_2 X^2 + g_3 X^3 \]

X: input; Y: output; \( g_{1,2,3} \) : linear gain/second/third-order nonlinearity coefficients

• Goal of linearization: make \( g_{2,3} \) small enough to be negligible, hence \( Y \approx g_1 X \)

• Two distortion sources for LNA:
  – Nonlinear transconductance \( g_m \), “input limited”
  – Nonlinear output conductance \( g_{ds} \), “output limited”
Outline

• Motivation
• Linearization Techniques
• New Issues for Wideband Applications
• LNA Linearization in Deep Submicron Process
• Remarks for High Linearity LNA Design
LNA Linearization Techniques

• Eight categories for the sake of discussion:
  – a) Feedback
  – b) Harmonic termination
  – c) Optimum biasing
  – d) Feedforward
  – e) Derivative superposition (DS)
  – f) IM2 injection
  – g) Noise/distortion cancellation
  – h) Post-distortion
## Distortion Sources & Corresponding Linearization Methods

<table>
<thead>
<tr>
<th>Linearization Methods</th>
<th>Distortion Sources</th>
<th>( g_m )</th>
<th>( g_{ds} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intrinsic 2(^{nd})-order</td>
<td>3(^{rd})-order</td>
<td>2(^{nd})-order interaction</td>
</tr>
<tr>
<td>Feedback</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Harmonic termination</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Optimal biasing</td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Feedforward</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Derivative superposition (DS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complementary DS</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Differential DS</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Modified DS</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>IM2 injection</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Noise/distortion cancellation</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Post-distortion</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
</tbody>
</table>
LNA Linearization Techniques

• Eight categories:
  – a) Feedback
    – b) Harmonic termination
    – c) Optimum biasing
    – d) Feedforward
    – e) Derivative superposition (DS)
    – f) IM2 injection
    – g) Noise/distortion cancellation
    – h) Post-distortion
a) Negative Feedback

- Nonlinear amplifier $A$:
  \[ Y = g_1 X + g_2 X^2 + g_3 X^3 \]

- Closed loop system:
  \[ Y_c = b_1 X + b_2 X^2 + b_3 X^3 \]

- $T_0 = g_1 \beta$: linear open-loop gain
- $b_{1,2,3}$: closed-loop linear gain and second/third-order nonlinearity coefficients

\[
Y_c = \frac{A \cdot x}{1 + \beta A} = \frac{A \cdot x}{1 + T}
\]
a) Negative Feedback

- IIP2 of the open-loop amplifier A: \[ A_{IIP2,amplifier} = \sqrt{\frac{g_1}{g_2}} \]
- IIP2 of the closed-loop system: \[ A_{IIP2,clolseloop} = \sqrt{\frac{b_1}{b_2}} = \sqrt{\frac{g_1}{g_2}(1+T_o)^2} \]
- IIP3 of the open-loop amplifier A: \[ A_{IIP3,amplifier} = \sqrt{\frac{4}{3}} \frac{g_1}{g_3} \]
- IIP3 of the closed-loop system: \[ A_{IIP3,closeloop} = \sqrt{\frac{4}{3}} \frac{b_1}{b_2} = \sqrt{\frac{4}{3}} \frac{g_1}{g_3} \left(\frac{1+T_o)^3}{1-\frac{2g_2^2}{g_1g_3}T_o} \right) \]
- Negative feedback improves \( A_{IIP2} \) by a factor of \((1+T_o)\); improves \( A_{IIP3} \) by a factor of \((1+T_o)^{3/2}\) when \( g_2 \approx 0 \);
- Nonzero \( g_2 \) degrades IIP3 when \( g_1 \) and \( g_3 \) have opposite signs

→ “2nd-order interaction”
a) Negative Feedback: Example

Inductively source-degenerated LNA:

\[ i_d = g_1(v_{in} - v_s) + g_2(v_{in} - v_s)^2 + g_3(v_{in} - v_s)^3 \]

\( v_s \neq 0 \), and contains components \( 2\omega_1, 2\omega_2 \), and \( \omega_1 \pm \omega_2 \) due to the 2\textsuperscript{nd}-order distortion

the product term \(-2g_2v_{in}v_s\) from \( g_2(v_{in} - v_s)^2 \) generates IM3 terms \( 2\omega_1 \pm \omega_2 \) and \( 2\omega_2 \pm \omega_1 \).

\( \Rightarrow \) the intrinsic 2\textsuperscript{nd}-order nonlinearity contributes to 3\textsuperscript{rd}-order intermodulation, IM3, when a feedback mechanism is employed.
a) Negative Feedback: Example

- Inductive source degeneration has two opposing effects on linearity:
  
  - 1) increases $A_{\text{IIP3}}$ by $\approx (1 + g_1 \omega L_s)^{3/2}$
  
  - 2) Degrades $A_{\text{IIP3}}$ due to “2nd-order interaction.”

$A_{\text{IIP3}}$ versus source-degeneration inductor $L_s$
a) Negative Feedback: Limitations

- Two sources for the 3\textsuperscript{rd}-order nonlinearity of an amplifier in feedback:
  - intrinsic amplifier 3\textsuperscript{rd}-order nonlinearity.
  - “2\textsuperscript{nd}-order interaction” (from intrinsic 2\textsuperscript{nd}-order nonlinearity \emph{combined with feedback}).

- Feedback for LNAs is not as effective as for baseband circuits because:
  - the open loop gain $T_0$ cannot be large due to stringent LNA gain, noise, and power requirement.
  - the 2nd-order nonlinearity contributes to the IM3 indirectly through “2nd-order interaction.”
LNA Linearization Techniques

• Eight categories:
  – a) Feedback
  – b) Harmonic termination
  – c) Optimum biasing
  – d) Feedforward
  – e) Derivative superposition (DS)
  – f) IM2 injection
  – g) Noise/distortion cancellation
  – h) Post-distortion
b) Harmonic Termination

- For frequency-dependent feedback network, using Volterra series to re-derive the feedback equation:

\[ b_3(\omega, \omega, -\omega - \Delta\omega) \approx \frac{1}{(1 + T(\omega))^3 (1 + T(-\omega))} \times g_3 - \frac{2g_2^2}{3g_1} \left( \frac{2T(\Delta\omega)}{1 + T(\Delta\omega)} + \frac{T(2\omega)}{1 + T(2\omega)} \right) \]

\[ T(\omega) = g_1\beta(\omega): \text{frequency-dependent linear loop gain} \]

Assuming two closely spaced input tones \( \omega_1 \) & \( \omega_2 \): for IM3 products at \( 2\omega_1 - \omega_2 \), \( -\omega_1 = \omega \), \( \omega_2 = -\omega - \Delta\omega \), \( \Delta\omega = \omega_1 - \omega_2 \approx 0 \)

- “2\text{nd}-order interaction” is determined by the loop gain at sub-harmonic frequency \( \Delta\omega \) & 2\text{nd}-harmonic frequency \( 2\omega \), i.e. \( T(\Delta\omega) \) and \( T(2\omega) \).
- by tuning the termination impedances at \( \Delta\omega \) and/or \( 2\omega \), the amplitude/phase of the 2\text{nd}-order interaction terms \( A_2 \) can be adjusted to cancel the intrinsic 3\text{rd}-order distortion term \( g_3 \).
b) Harmonic Termination

Three intrinsic feedback paths for Common source and Common gate LNAs

<table>
<thead>
<tr>
<th>Feedback Path</th>
<th>Path Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-LNA</td>
<td>CS-LNA</td>
</tr>
<tr>
<td>CG-LNA</td>
<td>CG-LNA</td>
</tr>
<tr>
<td>Source-to-gate</td>
<td>$C_{gs} + \text{source degeneration inductor } Z_2$</td>
</tr>
<tr>
<td>Drain-to-gate</td>
<td>$C_{gd} + \text{output load } Z_3$</td>
</tr>
<tr>
<td>Input-to-gate</td>
<td>Input matching network $Z_1$</td>
</tr>
</tbody>
</table>

- Resonant tanks can be added to G/D/S to optimally tune $Z_i(\Delta \omega)$ and/or $Z_i(2\omega)$ ($i=1-3$) such that the 2nd-order remixing term cancels the IM3 term.
- Commonly implemented with dedicated LC networks, which provide high impedance at $\omega$ but small impedance paths to ground at $\Delta \omega$ or $2\omega$. 
b) Harmonic Termination: Examples

- $L_t$ and $C_t$ form low-frequency/2nd-harmonic trap networks $Z_2(\Delta\omega, 2\omega)$
b) Harmonic Termination: Limitations

- Harmonic termination only works well in narrowband systems because the tuning network is optimized at $\Delta \omega$ and $2\omega$
- only works for a narrow range of two tone spacing/center frequencies [9].
- For wideband applications, $\Delta \omega$ and $2\omega$ vary considerably $\rightarrow$ difficult to tune out the termination impedance.
LNA Linearization Techniques

• Eight categories:
  – a) Feedback
  – b) Harmonic termination
  – c) Optimum biasing
  – d) Feedforward
  – e) Derivative superposition(DS)
  – f) IM2 injection
  – g) Noise/distortion cancellation
  – h) Post-distortion
c) Optimal Biasing

• To characterize the single-transistor nonlinearity, we fixed its $V_{ds}$, swept the $V_{gs}$, and then took the first three derivatives of $I_{ds}$ with respect to $V_{gs}$ at every DC bias point to obtain these plots:

NMOS transconductance characteristics
(UMC 90nm CMOS process, W/L = 20/0.08μm, Vds = 1V).
c) Optimal Biasing: Limitations

- Sensitive to PVT
- Limited input-signal amplitude range for effective distortion cancellation.
- A single transistor characteristic and only signifies optimum intrinsic 3rd-order gm nonlinearity; “sweet spot” is frequency-dependent, and the IIP3 peak decreases due to parasitic effects.
- Biasing the transistor at $g_3 = 0$ restricts the input-stage transconductance, lowering gain and increasing NF.
- Only works for fixed-gain LNAs (no AGC involved)
LNA Linearization Techniques

- Eight categories:
  - a) Feedback
  - b) Harmonic termination
  - c) Optimum biasing
  - d) Feedforward
  - e) Derivative superposition (DS)
  - f) IM2 injection
  - g) Noise/distortion cancellation
  - h) Post-distortion
d) Feedforward

• Cancellation of $g_2$ and/or $g_3$ with minimum effects on $g_1$ requires more degrees of freedom.
• generating additional nonlinear currents/voltages, and subsequently summing (subtracting) them accomplishes such cancellation.
• an auxiliary path includes a replica amplifier & signal-scaling factors $b$ & $1/b^n$ to replicate the distortion in the main path.
d) Feedforward: example

\[ Y_{\text{main}} = g_1 X + g_2 X^2 + g_3 X^3 \]

\[ Y_{\text{auxiliary}} = \left[ g_1 (bX) + g_2 (bX)^2 + g_3 (bX)^3 \right] \frac{1}{b^n} \]

\[ Y = Y_{\text{main}} - Y_{\text{auxiliary}} = g_1 \left( 1 - \frac{1}{b^{n-1}} \right) X + g_2 \left( 1 - \frac{1}{b^{n-2}} \right) X^2 + g_3 \left( 1 - \frac{1}{b^{n-3}} \right) X^3 \]

- gain-attenuation factor: \((1 - 1/b^{n-1})\), thus gain is reduced by 2.5dB with \(b = 2\) and \(n = 3\).
- only cancel one type of harmonic at a time; to reduce both 2\textsuperscript{nd}- & 3\textsuperscript{rd}-order distortion simultaneously, an additional degree of freedom is required \(\Rightarrow\) two auxiliary paths

Auxiliary Path

\(X \rightarrow b \rightarrow \frac{1}{b^n} \rightarrow Y\)
d) Feedforward: Limitations

- Accurate, noiseless, and highly linear scaling factors are often not feasible.
- Additional active components introduce more noise.
- Highly sensitive to mismatch between the main and auxiliary gain stages.
- Large power overhead due to the auxiliary amplifier. In worst case, the auxiliary amplifier is an exact copy of the main amplifier → double the power.
Feedforward: Special Cases

• Three special cases of the feedforward technique:
  – e) derivative superposition (DS)
    – Conventional DS
    – Complementary DS
    – Modified DS
  – f) IM2 injection
  – g) noise/distortion cancellation.
LNA Linearization Techniques

• Eight categories:
  – a) Feedback
  – b) Harmonic termination
  – c) Optimum biasing
  – d) Feedforward
  – e) Derivative superposition (DS)
  – f) IM2 injection
  – g) Noise/distortion cancellation
  – h) Post-distortion
e) Derivative Superposition (DS)

- A special case of the feedforward technique: obtained when $b=1$ and the main/auxiliary amplifiers are implemented with transistors in different regions or types.
- It adds the 3rd derivatives ($g_3$) of drain current from the main and auxiliary transistors to cancel distortion.
e) Conventional DS

- Linearity is improved within a finite bias-voltage range instead of just a point.
e) Complementary DS

- The 2\textsuperscript{nd}-order term \((g_2)\) always has a positive sign: conventional DS improves 3\textsuperscript{rd}-order distortion but worsens 2\textsuperscript{nd}-order distortion.

- “Complementary DS method” employs an NMOS/PMOS pair to improve IIP3 without hurting IIP2

\[
\begin{align*}
    i_{dsn} &= g_{1A} v_{gs} + g_{2A} v_{gs}^2 + g_{3A} v_{gs}^3 \\
    i_{dsp} &= -g_{1B} v_{gs} + g_{2B} v_{gs}^2 - g_{3B} v_{gs}^3 \\
    i_{out} &= i_{dsn} - i_{dsp} = (g_{1A} + g_{1B}) v_{gs} + (g_{2A} - g_{2B}) v_{gs}^2 + (g_{3A} + g_{3B}) v_{gs}^3
\end{align*}
\]

- Total transconductance increases; IM2 term decreases because \(g_{2A}\) and \(g_{2B}\) have the same sign; IM3 term decreases because \(g_{3A}\) and \(g_{3B}\) have different signs.
e) Complementary DS: Examples

Common-source configuration

Common-gate configuration
e) Complementary DS vs. Conventional DS

- $g_2$ is maximized for conventional DS & minimized for complementary DS.
- The $g_3$ cancellation window is narrower and less flat for complementary DS since PMOS and NMOS devices have different linearity characteristics.

Comparison of conventional (dual-NMOS) DS and complementary (PMOS/NMOS) DS: (a) $g_2$ vs. $V_{gs}$ (b) $g_3$ vs. $V_{gs}$ (UMC 90nm CMOS process, $V_{ds} = 1V$).
e) Modified DS

- Motivation: the “2nd-order interaction” ultimately limits the IIP3 at higher frequencies, after the intrinsic $g_3$-induced 3rd-order distortion is cancelled by the DS method.

- Three feedback paths exist for “2nd-order interaction”: source-to-gate, drain-to-gate, and input-to-gate.

- The modified DS methods minimize the source-to-gate feedback → reducing 2nd-order interaction
e) Modified DS vs. Conventional DS

- Conventional DS: the anti-parallel $g_{3A}$ and $g_{3B}$ result in a zero total $g_3$, but residual IM3 exists due to $g_{2A}$ contributions.

- Modified DS: $g_{3B}$ is rotated properly such that the composite vector of $g_{3A}$ and $g_{3B}$ contribution is $180^\circ$ out of phase with the $g_{2A}$ contribution, yielding zero net IM3.

![Conventional DS method](image1)

![Modified DS method](image2)
e) Modified DS: Examples

(a)

(b) source-sensed
e) Modified DS: Limitations

- The weak-inversion transistor may not operate at very high frequency; cannot handle large signals or it will be turned off, → very limited distortion-cancellation range.
- Weak-inversion transistor models are generally not accurate → discrepancy between simulation & measurement.
- Matching transistors working in different regions is difficult → a linearity improvement sensitive to PVT variations.

![Graph showing Measured IIP3 with/without DS method.](https://via.placeholder.com/150)
LNA Linearization Techniques

• Eight categories:
  – a) Feedback
  – b) Harmonic termination
  – c) Optimum biasing
  – d) Feedforward
  – e) Derivative superposition(DS)
  – f) IM2 injection
  – g) Noise/distortion cancellation
  – h) Post-distortion
f) IM2 Injection

- Eliminates the explicit auxiliary path by merging it with the main path to reuse the active devices and the DC current.
- Externally generates and injects a low-frequency IM2 component into the circuit.
- Key idea: tune the amplitude & phase of the injected IM2 current for optimal distortion cancellation.
f) IM2 Injection: Implementation

- M4, M5, R, and C compose a squaring circuit to generate a low-frequency IM2 current at $\omega_2 - \omega_1$, which is then injected through M3 into the common source node $v_s$.

- Design equation:

$$-(\frac{2g_1g_3}{4g_2}) + \left(\frac{3}{2}\right)g_2 = g_{1,M3}\left(-2g_{2,M1}\right)R$$
f) IM2 Injection: Limitations

- NMOS/PMOS transistors and resistors have independent PVT variations \(\rightarrow\) difficult to satisfy the IM3 cancellation criteria robustly.
- R and C in the IM2 generator introduce extra phase shift, two tone spacing must be smaller than the RC-filter cutoff frequency for negligible phase mismatch. Cancellation performance degrades as tone spacing increases.
- Frequency components at \(\omega_2 \pm \omega_1\) and \(2\omega_{1,2}\) injected by the IM2 generator may fall into signal band and degrade the IIP2.
- Noise from the IM2 generator is negligible only for differential LNAs,
- In short, IM2 injection applies chiefly to narrowband, differential systems with small two-tone spacing.
LNA Linearization Techniques

• Eight categories:
  – a) Feedback
  – b) Harmonic termination
  – c) Optimum biasing
  – d) Feedforward
  – e) Derivative superposition (DS)
  – f) IM2 injection
  – g) Noise/distortion cancellation
  – h) Post-distortion
g) Noise/Distortion Cancellation

- Design equations:
  \[ g_{1,M_A} R_A = g_{1,M_B} R_B \]
  \[ g_{1,M_{B1}} R_s = g_{1,M_{B2}} R_A \]
g) Noise/Distortion Cancellation

• Requirement: the two paths through $M_A$ and $M_B$ are balanced for the noise/distortion current
• can cancel all intrinsic distortion generated by $M_A$, including both $g_m$ and $g_{ds}$ nonlinearity
• Limitation: after cancelling the distortion from $M_A$, $M_B$’s distortion dominates the residual nonlinearity, which comprises two terms: 1) $M_B$’s intrinsic 3rd-order distortion and 2) 2nd-order interaction originating from the CG-CS cascade.
LNA Linearization Techniques

• Eight categories:
  – a) Feedback
  – b) Harmonic termination
  – c) Optimum biasing
  – d) Feedforward
  – e) Derivative superposition(DS)
  – f) IM2 injection
  – g) Noise/distortion cancellation
  – h) Post-distortion
h) Post-Distortion (PD)

- Similar to the DS method, the PD method also uses an auxiliary transistor’s nonlinearity to cancel that of the main device, but it is more advanced in two aspects:
  - The auxiliary transistor is connected to the output of main device, minimizing the impact on input matching.
  - All transistors operate in saturation, resulting in more robust distortion cancellation.
Model the nonlinear drain currents of $M_A$ & $M_B$ as:

\[ i_A = g_{1A}v_1 + g_{2A}v_1^2 + g_{3A}v_1^3 \]

\[ i_B = g_{1B}v_2 + g_{2B}v_2^2 + g_{3B}v_2^3 \]

Next, suppose $v_2$ is related to $v_1$ by:

\[ v_2 = -b_1v_1 - b_2v_1^2 - b_3v_1^3 \]

The two nonlinear currents $i_A$ and $i_B$ sum at node $v_2$, yielding $i_{out}$:

\[ i_{out} = i_A + i_B = \left( g_{1A} - b_1g_{1B} \right)v_1 \]

\[ + \left( g_{2A} - b_1^2g_{2B} - b_2g_{1B} \right)v_1^2 + \left( g_{3A} - b_1^3g_{3B} - g_{1B}b_3 - 2g_{2B}b_1b_2 \right)v_1^3 \]

2nd-order distortion

3rd-order distortion
h) PD: Implementations

- Auxiliary transistor \( M_B \) taps voltage \( v_2 \) and replicates the nonlinear drain current of the main transistor \( M_A \), partially cancelling both 2\(^{nd}\)- and 3\(^{rd}\)-order distortion terms.

- Three examples of PD implementations:
## Distortion Sources & Corresponding Linearization Methods

<table>
<thead>
<tr>
<th>Linearization Methods</th>
<th>Distortion Sources</th>
<th>$g_m$</th>
<th>$g_{ds}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intrinsic 2\textsuperscript{nd}-order</td>
<td>Intrinsic 3\textsuperscript{rd}-order</td>
<td>2\textsuperscript{nd}-order interaction</td>
</tr>
<tr>
<td>Feedback</td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harmonic termination</td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Optimal biasing</td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Feedforward</td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Derivative superposition(DS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complementary DS</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Differential DS</td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified DS</td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>IM2 injection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise/distortion cancellation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-distortion</td>
<td>√</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Linearization Techniques: Summary

<table>
<thead>
<tr>
<th>Linearization Technique</th>
<th>Harmonic Termination</th>
<th>Optimum biasing</th>
<th>Feedforward</th>
<th>Derivative Superposition</th>
<th>Modified DS</th>
<th>Complementary DS</th>
<th>IM2 Injection</th>
<th>Noise/Distortion Cancellation</th>
<th>Post Distortion</th>
<th>Power</th>
<th>Supply Voltage</th>
<th>Frequency</th>
<th>Process</th>
<th>Robustness over PVT</th>
<th>Wideband?</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>IIP3/ Δ IIP3</em></td>
<td>-4.4dBm/+2.5dBm</td>
<td>+10.5dBm</td>
<td>5dBm/+13dB</td>
<td>2.7dBm/+13.4dB</td>
<td>2dBm/+20dB</td>
<td>3dBm</td>
<td>-10.4dBm/+10.6dB</td>
<td>&gt;0dBm</td>
<td>5dBm/+9dB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>IIP2/ Δ IIP2</em></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>+44dBm</td>
<td>N/A</td>
<td>&gt;+20dBm</td>
<td>+10dBm</td>
<td>14.3dB/-1.7dB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Gain/ Δ Gain</em></td>
<td>20.4dB/+2dB</td>
<td>14.6dB/0dB</td>
<td>18dB/-2.5dB</td>
<td>15.3dB/-0.4dB</td>
<td>16dB/-0.5dB</td>
<td>14dB</td>
<td>22dB/0dB</td>
<td>13-15.6dB</td>
<td>14.3dB/-1.7dB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>NF/ Δ NF</em></td>
<td>1.92dB/0dB</td>
<td>1.8dB/0dB</td>
<td>2.6dB/0.2dB</td>
<td>2.9dB/0.1dB</td>
<td>1.4dB/0.25dB</td>
<td>3dB</td>
<td>5.3dB/0dB</td>
<td>&lt;3.5dB</td>
<td>2.7dB/+0.6dB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power/ Δ Power</td>
<td>16.2mW/0%</td>
<td>5.4mW/0%</td>
<td>22.5mW/100%</td>
<td>20mW/17.5%</td>
<td>23.4mW/3.4%</td>
<td>34.8mW</td>
<td>19.6mW/0.7%</td>
<td>14mW</td>
<td>2.6mW/+1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>1.8V</td>
<td>2.7V</td>
<td>3.0V</td>
<td>2.5V</td>
<td>2.6V</td>
<td>2.2V</td>
<td>1.5V</td>
<td>1.2V</td>
<td>1.3V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>2.2GHz</td>
<td>880MHz</td>
<td>900MHz</td>
<td>2.2GHz</td>
<td>900MHz</td>
<td>48-1200MHz</td>
<td>900MHz</td>
<td>0.2-5.2GHz</td>
<td>2.5-10GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process</td>
<td>0.35μm</td>
<td>0.25μm</td>
<td>0.35μm</td>
<td>0.35μm</td>
<td>0.25μm</td>
<td>0.18μm</td>
<td>0.18μm</td>
<td>65nm</td>
<td>0.13μm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robustness over PVT</td>
<td>moderate</td>
<td>poor</td>
<td>good</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
<td>good</td>
<td>good</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wideband?</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Outline

• Motivation
• Linearization Techniques
• New Issues for Wideband Applications
  • LNA Linearization in Deep Submicron Process
  • Remarks for High Linearity LNA Design
Growing research on multi-standard/UWB transceivers has sparked increased interest in wideband LNA design.

- Hundreds of channels enter the receiver without any pre-filtering, acting as in-band interferers, creating severe distortions → High Linearity is needed!
New Issues for Wideband Applications
New Issues for Wideband Applications

• Three main concerns:
  – IIP2
  – P1dB
  – IIP2/IIP3 vs. two-tone frequency and spacing IM3 asymmetry
IIP2

- Narrowband system: the 2\textsuperscript{nd}-order nonlinearity is generally out of band
- Wideband receivers: many channels are present concurrently and act as in-band interferences: the IM2 products generated by certain combination of interferences fall into the signal band.
- Broadband LNAs should have a good IIP2 as well as IIP3.
IIP2 Improvement Methods

- Fully differential LNA
- Complementary/differential DS method
- Post-distortion
- Biasing a CS-stage at the maximum gain in deep submicron process
• In wideband receivers, LNAs receive the accumulated power from multiple channels, which could range from -10 to 0dBm.

• Wideband LNAs are desired to have a high signal-handling capability, i.e. high $P_{1dB}$, to prevent desensitization, gain compression, and clipping.

• IIP2/IIP3-improvement techniques typically only work over small signal ranges, and do not improve $P_{1dB}$ because it is a large-signal parameter.
$P_{1\text{dB}}$ Improvement Methods

- Increasing $V_{dd}$ above nominal values to maximize the voltage headroom
- Using low-$f_T$, thick-oxide transistors to handle larger voltage swings to allow even larger $V_{dd}$.
- Cancel higher-order distortion, e.g. IM5 & IM7
- Extend the effective input range of IM2/IM3 cancellation;
- Add source degeneration at the cost of extra noise.
- Dynamic bias/dynamic supply
- Reduce the output voltage swing to relax the limitation from nonlinear output conductance.
IIP2/IIP3 vs. Two-tone Frequency and Spacing

- Broadband LNAs should have relatively flat IIP2/IIP3 over the signal band
- IIP2/IIP3 should be examined at various two-tone-spacing and center frequencies
- Reactive components (e.g. those in the matching network) causes frequency dependence of IIP2/IIP3
IIP2/3 dependency on two-tone-spacing

- “2\textsuperscript{nd}-order interaction”
- Large two-tone spacing
- Narrowband IM2 cancellation scheme
- Variations of $\Delta \omega$ cause the optimum point of the 2\textsuperscript{nd}-order interaction cancellation to change, resulting in worse linearity.
- “IM3 asymmetry” due to memory effects

\[ H_2(2\omega_1) \]
\[ H_2(\omega_2 - \omega_1) \]
\[ H_3(2\omega_1 - \omega_2) \]
\[ H_1(\omega_1), H_1(-\omega_2) \]
\[ H_1(\omega_2), H_1(-\omega_1) \]
\[ H_3(2\omega_2 - \omega_1) \]
\[ H_2(2\omega_2) \]

Re
Im

Lower IM3 Vector

Upper IM3 Vector
Outline

• Motivation
• Linearization Techniques
• New Issues for Wideband Applications
• LNA Linearization in Deep Submicron Process
• Remarks for High Linearity LNA Design
LNA Linearization in Deep submicron Technology

• Nonlinearity from output conductance $g_{ds}$
• Impact of Technology Scaling on Linearity
Nonlinearity from output conductance $g_{ds}$

- $g_{ds}$ nonlinearity becomes more prominent in scaling down technology
- Current $i_{ds}$ is controlled by both $V_{gs}$ and $V_{ds}$, approximated by the two-dimensional Taylor series:

$$i_{ds}(V_{gs}, V_{ds}) = g_1 V_{gs} + g_2 V_{gs}^2 + g_3 V_{gs}^3 + g_{ds1} V_{ds} + g_{ds2} V_{ds}^2 + g_{ds3} V_{ds}^3 + c_{(1,1)} V_{gs} V_{ds} + c_{(2,1)} V_{gs}^2 V_{ds} + c_{(1,2)} V_{gs} V_{ds}^2$$

$$g_{dsi} = \frac{1}{i!} \frac{\partial^i I_{DS}}{\partial V_{DS}^i} \quad c_{(m,n)} = \frac{1}{m!n!} \frac{\partial^{m+n} I_{DS}}{\partial V_{GS}^m \partial V_{DS}^n}$$
**g_{ds} Nonlinearity Characteristics**

- Fix \( V_{gs} \) at 0.5V, sweep the \( V_{ds} \), by taking the first three derivatives of \( i_{ds} \) with respect to \( V_{ds} \) at every DC bias point, we obtained:

- \( g_{ds3} \) is large when the transistor operates at small \( V_{ds} \); it decreases for large \( V_{ds} \) values.

- \( g_{ds} \) contributes less nonlinearity when device operates deeper into saturation region.

**NMOS output conductance nonlinearity characteristics**

(UMC 90nm CMOS process, \( W/L = 20/0.08\mu m \), \( V_{gs} = 0.5V \), \( V_{th} = 0.26V \)).
Impact of Technology Scaling

- $g_{ds}$ is more nonlinear for shorter channel length
- Reduced supply $\rightarrow$ device biased closer to the triode-saturation boundary, worsens $g_{ds}$ nonlinearity.
- “sweet spot” systematically shift to higher bias-current density $I_{ds}/W \rightarrow$ requires larger power to preserve linearity.
- Oxide thickness decreases, poly-gate depletion increases, nonlinear gate capacitance develops strong 2nd-order derivatives with respect to $V_{gs} \rightarrow$ significant 3rd-order distortion
- Key challenge: deliver high linearity with core transistors and with a low supply voltage in the DSM processes.
Outline

- Motivation
- Linearization Techniques
- New Issues for Wideband Applications
- LNA Linearization in Deep Submicron Process
- Remarks for High Linearity LNA Design
To reduce $g_{ds}$-induced distortion

- Increasing supply voltage mitigates the $g_{ds}$ effect, allows larger output swing and hence improves $P_{1dB}$.
- With sufficient voltage headroom, adding cascode device allows $g_{ds} \ll R_{Load}$, yielding a more linear output load.
- Bias the cascode transistor at smaller $V_{gs}$ (i.e. lower overdrive voltage) to tolerate a larger swing at the drain.
- Reducing the load resistance of the LNA (which may affect the design of other building blocks in the receiver)
Other Tips

• For inductively degenerated CS-LNAs: reduce Q to mitigate the “Q boosting” effect, provided enough margin in NF and gain. Add external capacitor in parallel with $C_{gs}$ to allow more freedom for input transistor sizing.

• CG-LNAs generally provide better linearity than CS-LNAs

• Use cascode transistors whenever possible to:
  – reduce 2nd-order interaction through $C_{gd}$
  – reduce the voltage swing across each active device, improving reliability for DSM devices.
Conclusions

• Reviewed eight categories of CMOS LNA linearization techniques and discussed the tradeoffs among linearity, power, and PVT variations.
• Discussed wideband LNA-linearization issues for the emerging broadband transceivers
• Examined issues in deep submicron processes
• Presented general design guidelines for high-linearity LNAs.
References


References

Harmonic termination


References

Optimum biasing

Feedforward

Derivative Superposition (DS)
Complementary DS

Differential DS

Modified DS

IM2 injection
### Noise/Distortion Cancellation


### Post-distortion


References

IIP2 calibration


IIP2/IIP3 dependence on two tone spacing


Others


LNA linearization in deep submicron technology


